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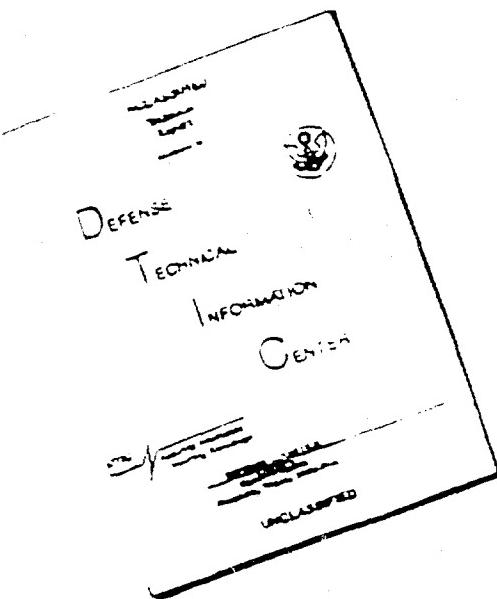
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ARL 63-45

FEBRUARY 1963

ERRATA - AUGUST 1963

Please substitute the attached cover page for ARL 63-45 entitled "A Versatile Apparatus for the Study of Refractory Index Fields in Cases," dated February 1963.

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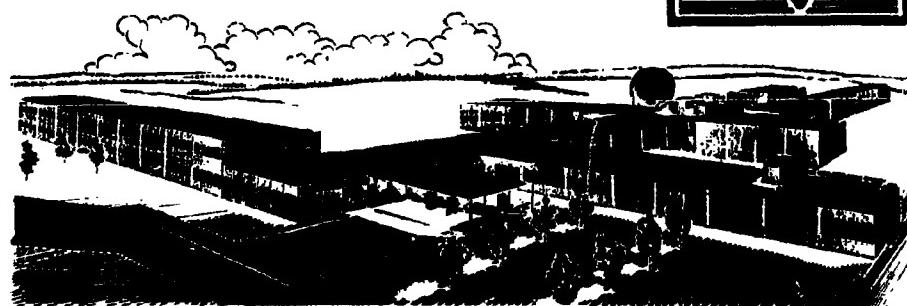
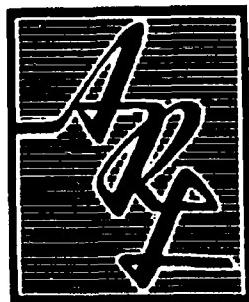
ARL 63-45

A VERSATILE APPARATUS FOR THE STUDY OF REFRACTIVE INDEX FIELDS IN GASES

F. J. WEINBERG
CHEMISTRY RESEARCH LABORATORY

FEBRUARY 1963

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ARL 63-45

**A VERSATILE APPARATUS FOR THE STUDY OF
REFRACTIVE INDEX FIELDS IN GASES**

**F. J. WEINBERG
CHEMISTRY RESEARCH LABORATORY**

FEBRUARY 1963

**CONTRACT AF 33(616)-7022
PROJECT 7013
TASK 7013-04**

**AERONAUTICAL RESEARCH LABORATORIES
OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO**

FOREWORD

This technical report was prepared by Dr. F. J. Weinberg of the Imperial College of Science and Technology, South Kensington, London, S. W. 7, England, during his stay at the Aeronautical Research Laboratories, as a visiting scientist in July 1962. It covers a part of the in-house research effort on Task 7013-01, "Research on Energetic Processes in Gases" of Project 7013, "Research in Chemical Energetics".

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A relatively inexpensive optical system is described which is capable of interferometry deflection mapping, shadowgraphy and the entire range of schlieren recording. It is easy to set up, requires only minor adjustments to convert it from one function to another and, when desired, can fulfill several of them simultaneously. Its construction is discussed and illustrated by a variety of records.

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**A VERSATILE APPARATUS FOR THE STUDY OF
REFRACTORY INDEX FIELDS IN CASES**

**F. J. WEINBERG
CHEMISTRY RESEARCH LABORATORY**

FEBRUARY 1963

**CONTRACT AF 33(616)-7022
PROJECT 7013
TASK 7013-04**

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ABSTRACT

A relatively inexpensive optical system is described which is capable of interferometry, deflection mapping, shadowgraphy and the entire range of schlieren recording. It is easy to set up, requires only minor adjustments to convert it from one function to another and, when desired, can fulfill several of them simultaneously. Its construction is discussed and illustrated by a variety of records.

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INTRODUCTION

The variations in the refractive index of gases which are occasioned by changes in temperature, composition and/or pressure, form the basis of a large family of optical methods in combustion, aerodynamics and allied fields. The methods have two main aims: making visible changes in gas density by the light of an external source and the measurement of refractive index distributions for analytical studies. The former involves techniques such as shadowgraphy and the large family of schlieren methods; the latter employs quantitative (e. g. Ronchi) schlieren methods, deflection mapping, or interferometry.

In principle, all these methods either measure, or in some way visualize, the topography of an initially plane wave-front of light, after its distortion by passage through the working section. Interferometry records contour lines, one wavelength apart, resulting from shearing the distorted wave front with an unperturbed one. The methods of geometric optics measure, or record, the deflection of "rays" - i. e., the slope of the hills and valleys on the wave front. It follows that the choice of the best method must, in each case, be determined by the extent and rapidity of the variation in optical path across the test space. A gradual variation will be recorded most accurately by interferometry. Large slopes, particularly if they extend over small regions, are recorded more accurately by "ray" deflection measurement. This may be so either because the absolute size of the perturbations on the emergent wave front are small, or because the large deflections impair the accuracy of interferometry, or for both these reasons. In the case of the steepest slopes, the recording of the second derivative of the optical path, by shadowgraphy, may become the most sensitive method of visualization.

While the optimum ranges of the various techniques fortunately overlap, the most suitable method may not be known *a priori*, even for one particular phenomenon. If the apparatus is to cater for an unknown range of test objects, the facility of applying various methods becomes most desirable. Accordingly, the purpose of the present work is to establish a single optical system capable of interferometry, shadowgraphy, deflection mapping by all the various techniques, and of producing the entire range of schlieren records. At the same time, the apparatus is to be relatively inexpensive, easy to set up and adjust, and should cover an adequate test area.

APPARATUS

The system developed involves and combines so large a number of principles (Refs 1-22), many of which have previously been discussed individually, that it would be too wasteful of space to trace its parentage. A schematic diagram is shown in Figure 1.

Referring to Plan I, A is the light source - in the present instance a high pressure mercury arc. B is a condenser focused on a pin-hole, C, which becomes the effective source of the system. The angle subtended by B at C just fills lens D - here a doublet collimator of 13 cm focal length - which produces an image of the pin-hole at F. E is a suitable position for a filter, when monochromatic illumination is required.

When the system is used as an interferometer (Refs 18-22), F is a reflection grating arranged so that the zero order fills one, and the first order the other, half of the schlieren mirror G. If (a/f) is the angle subtended by the radius of the schlieren mirror at F, its focal point, this implies that the angle subtended there

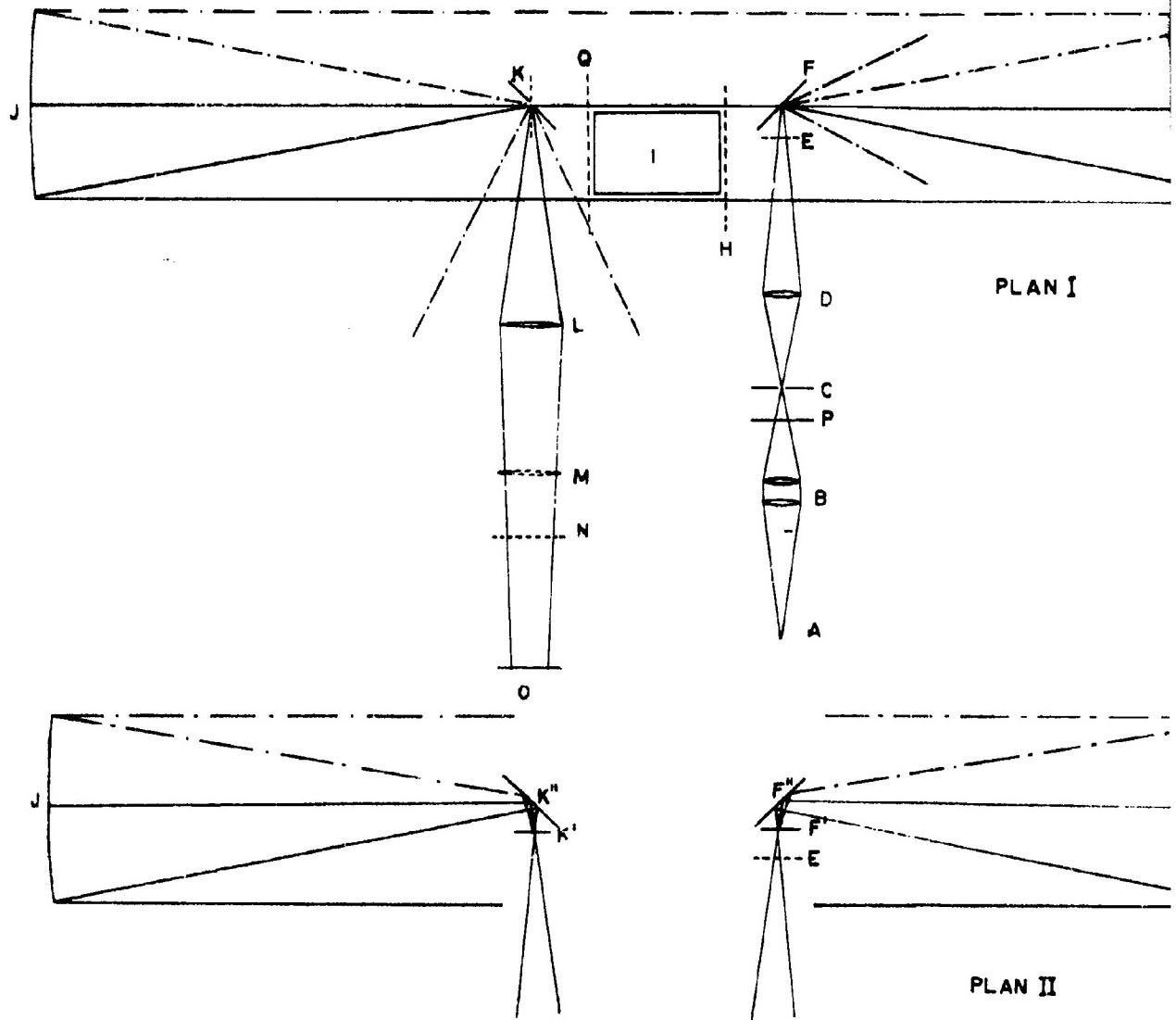
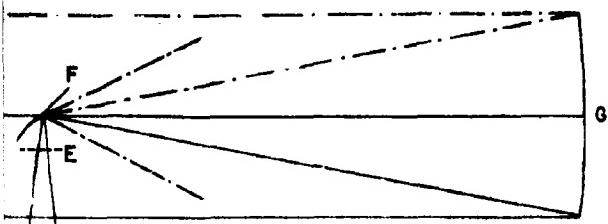
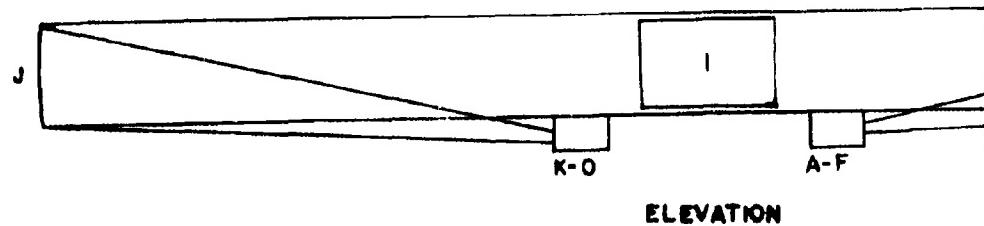
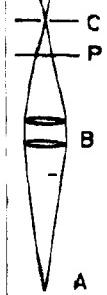


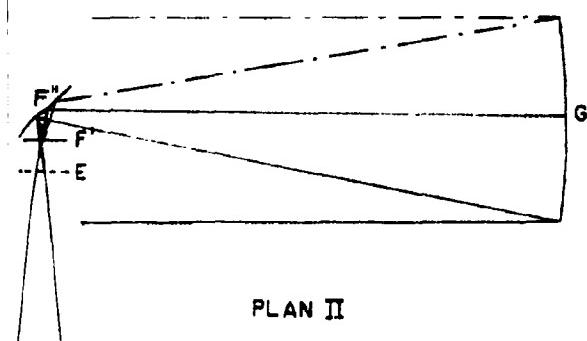
Figure 1. Schematic diagram of optical system



PLAN I



ELEVATION

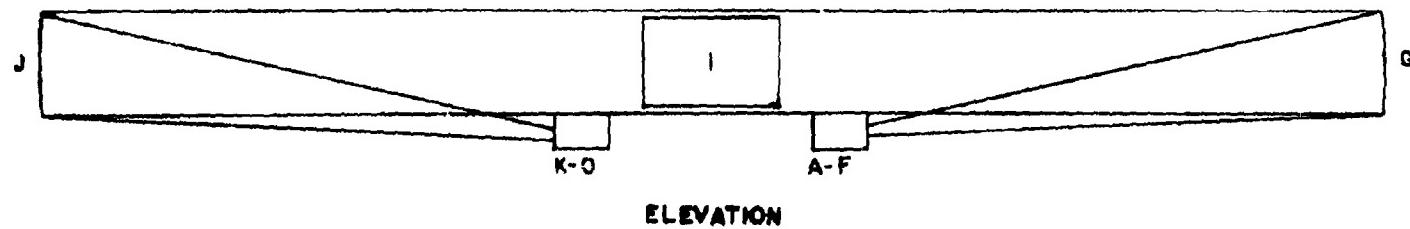
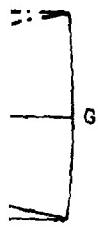


PLAN II

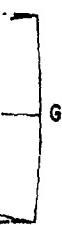
cal system



1



ELEVATION



3

there by D must also be (a/f) and that the groove spacing of the grating should be $\lambda / \sin(a/f) \approx \lambda f/a$, (λ = wave length). Under these conditions, the schlieren mirror, G, will be exactly filled by the circles of the first and second orders, touching at the center of the mirror. After being rendered parallel by the mirror, these two beams become the test and the reference paths. The blazing of the grating should be such that the energy flux in the two beams is approximately equal (although fringe legibility need not be impaired if this is not done, since inequality in illumination can be compensated at the second grating). In this manner the field of view of the interferometer is a circle of half the diameter of the mirror.

If desired, the working space can be increased somewhat in one direction by doubling the angle subtended by D at F and cutting off half the aperture by a stop somewhere between D and F. The dimensions of the field of view in the two arrangements are illustrated in Figure 2.

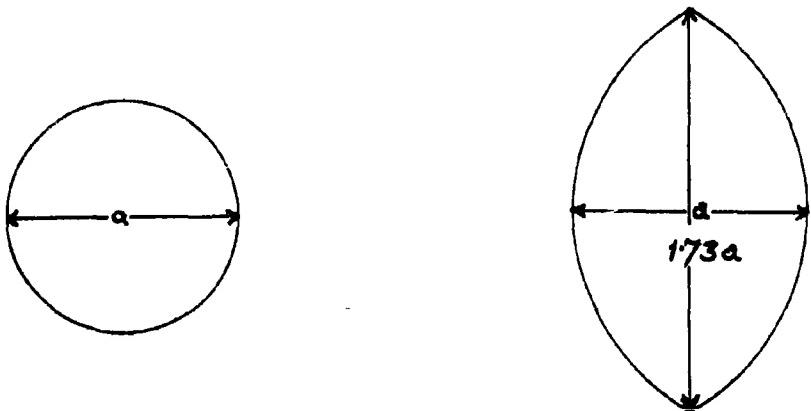


Figure 2. The dimensions of the field of view.

When the system is used for schlieren or deflection mapping work, the grating at F can be replaced by a front-surfaced mirror. This will save erosion of the grating, increase illumination, and allow use of the whole aperture of the schlieren mirror (by doubling the angle subtended by D at E) if the extent of the working space, I, demands it.

It is convenient to have the two schlieren mirrors, G and J, of identical optical properties - in the present instance 12.0 cm radius and 259 cm focal length. The parallel beam between them is arranged so as just to clear K and F, by folding the optical axis through a very small angle in the vertical plane (see elevation, Figure 1).

K is at the focus of J. When the system is used as an interferometer, K is a second reflection grating of the same specification as the first. Recombination of the wave fronts and interference, takes place in all its orders. The grating should be oriented in such a way with respect to its blazing profile that, in the beam reaching the receptor, O, it compensates for any difference in intensity between the test and the reference beam which may have been introduced by the first grating. Displacement of the grating from the focus replaces the infinite fringe condition by a finite angle between the wave fronts. It can be shown (Refs 18, 20) that the fringe spacing, g is given by

$$g = \frac{fd\sqrt{1-(\lambda/d)^2}}{\Delta x}$$

where d is the groove spacing of the grating, Δx its displacement from the focus, and λ the wave length. Since

$$(\lambda/d)^2 \ll 1$$

the interferometer has the usual property of separating the fringes of all wave

lengths almost equally and thus producing a wide field of white light fringes.

For schlieren methods (Refs 1-10, 17-18) (here defined as methods in which I is focused on O and some kind of "schlieren aperture", at K, marks deflected "rays" by a change in illumination, color, etc.), a front-silvered mirror is used at K. The various "schlieren apertures" can then be drawn on, or attached to, the surface. The advantage of this scheme is that, by moving the mirror in its own plane, using a screw-thread adjustment, the several schlieren "services" can be deployed one after the other, without altering anything else in the system. In the present arrangement, the several "schlieren apertures", drawn in black ink upon the surface, included horizontal and vertical "knife edges"; a circular aperture; a circular stop; grids and concentric rings for unidirectional and axisymmetric "Ronchi schlieren". Strips of colored gelatine filters were attached to the surface for color schlieren. Care must be taken to leave enough of the mirror area free to ensure that the deflection pattern there does not overlap the edges, so that the system can be used for shadowgraphy or deflection mapping.

In order that the polar distribution of deflections in the test space can be studied, the mirror at K may be replaced by a screen, or photographic plate, at right angles to the incident beam. Any part of the test space may be examined in this way by isolating it by means of an aperture placed at H. Specialized uses of such records have been discussed elsewhere (Ref 9). If such a photograph is to be used directly as a selective schlieren aperture - in order to suppress or enhance the visualization of one particular phenomenon in the presence of others - the photographic plate should be exposed while attached to the mirror and used in this position after development. The reason is that the polar diagram must, of

course, be appropriately distorted for use at 45° incidence.

The lens L - a 127 cm focal length achromat, in the present instance - is positioned to focus I on O (through J) for all schlieren and interferometric, and some deflection mapping, applications. A large focal length is necessary, if a large image is to be produced (Ref 18) at O. For shadowgraphy and certain deflection mapping work, the system must be de-focused and this is most conveniently carried out, without increasing the length of the system, by moving this projection lens. The distances should be so chosen that the maximum de-focusing required occurs with the lens at M.

The receptor, O, is a ground glass screen, interchangeable for a photographic plate, or film, which is used in conjunction with the shutter at P. H, Q and N are suitable positions - depending on the system used - for a grid, a plate of half-wave steps, or other device marking the wave front for deflection mapping. The utility of such devices is discussed below.

Plan II shows a modification (Ref 19) of the interferometer system, which is based on transmission gratings. It differs from the one above only in that the diffracting and reflecting functions of the reflection gratings have been separated and taken up by two transmission gratings (F' and K') and by two mirrors (F'' and K''), respectively. Since the gratings must be at the foci of the schlieren mirrors, J and G are displaced inward by the appropriate distance.

This system has several advantages over that described above, and these become particularly pronounced when gratings of the ideal specifications (discussed above) are difficult to obtain. In the present instance, a simple and speedy method of producing replicas in "Plexiglass" was developed by Dr. U. Grimm and by this

means adequate transmission gratings were obtained, at virtually no cost, from a master kindly loaned by The Ohio State University. The somewhat dubious optical qualities of "Plexiglass" are rendered unimportant by the properties of the interferometer. The gratings are oriented with their rulings inward (this still allows them to be adjusted for maximum fringe visibility) so that the beams transverse their thickness only before splitting and after recombination. Moreover, the beams are focused at the points of traversal, so that only a very small area of each grating is involved. The effective spacing of the grooves can be altered by small amounts by rotating the grating somewhat, about an axis parallel to the ruling. This is most conveniently carried out on the second grating, using the appearance of the fringes as a guide. It can be shown (Ref 21) that the direction of the diffracted beams is barely affected by small changes in angle of incidence, in the case of a transmission grating. This degree of freedom is, however, not available in the case of reflection gratings, the rotation of which also rotates the optic axis after diffraction. (It should, however, not be required if the gratings are perfect.)

The use of "home-made" replicas, which are so cheap that it does not matter if they occasionally become damaged, makes it possible and convenient to attach and/or draw the various schlieren apertures directly onto the grating. Thus the system becomes instantly convertible from an interferometer to a shadow or schlieren device. (If it is desired to eliminate any background of fringes while the system is used in one of these capacities, it is merely necessary to obscure the reference beam at F'' for K'' .) It is therefore just as versatile as the form discussed above, in which the "schlieren services" were attached to the plane

mirror, and has the marginal advantage that the polar diagram of deflection is produced in a plane perpendicular to the optic axis.

METHODS OF USE

TEST FIELDS

Applications of the system are illustrated with reference to three test objects: (1) a bunsen burner flame, heating a 1-inch length of tubing with its axis parallel to the beam; (2) the same hot piece of tubing surrounded by cold air; (3) the flame on a wing top burner with its plane parallel to the beam; (4) a grating of 60 lines in. These provide a suitable variety of optical path distributions, typical of those encountered in combustion and heat transfer research. In (2), the optical path gradients can be made as small as necessary for the purpose of illustration by decreasing the temperature of the pipe. In (3), very appreciable gradients can be produced. (4) provides an example of a diffraction-induced displacement of the "rays", which occurs entirely in one plane. The test objects will be referred to by the above numbers.

SHADOWGRAPHY (Refs 11, 12, 13, 18)

It is merely necessary to de-focus the system, in the absense of any marking aperture at K, to record shadowgrams. The variable is the extent of de-focusing, which determines the magnitude of displacement of deflected rays, and therefore the sensitivity of the system. The adjustment is most conveniently made by moving lens L. It is not desirable to use the system at maximum sensitivity at all times. The bright lines, which are caused by light deflected away from the regions which appear dark, should not be too far removed from their positions of origin. Figure 3 is a shadowgram of test object (1), with lens L positioned at

M, for which the de-focusing was too large. The displacement of the light from the dark regions is such as to obscure the structure of the phenomenon. This has been remedied in Figure 4, where the sensitivity has been matched to the deflection field and adequate visualization is achieved.



Figure 3. Shadow far from focus. Considerable displacement of light.

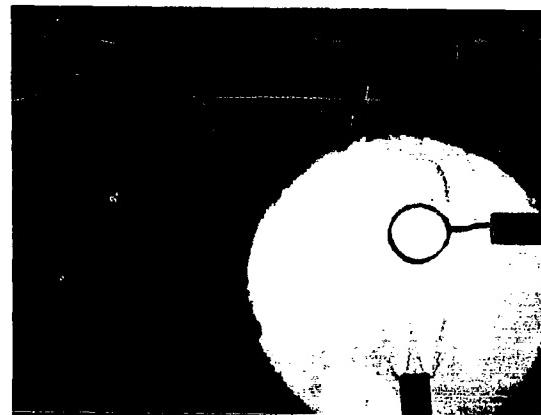


Figure 4. Shadow near focus. Correct small light displacement.

All the test objects were used without an enclosure and windows, which made it necessary to suppress air currents. The effects of not switching off the air-conditioning in the room is shown in Figure 5, which, like the other exposures, was taken at 1/400 sec.



Figure 5. Effect of air conditioning (Shadow).

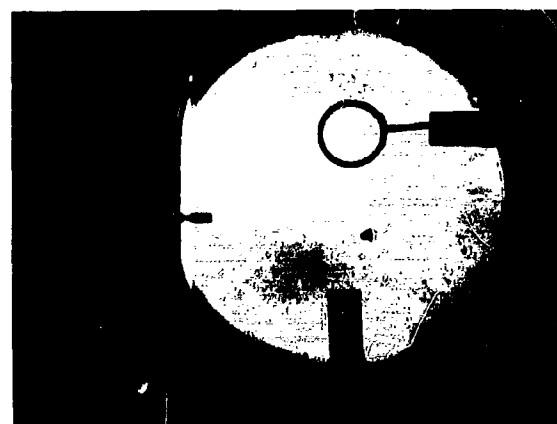


Figure 6. At the focus. No shadows.

When the system is in focus, all shadows, of course, disappear, because all rays passing through each point of the object are re-united on the conjugate point of the image, irrespective of their original directions (Figure 6).



Figure 7. Vertical knife-edge marking horizontal deflections.

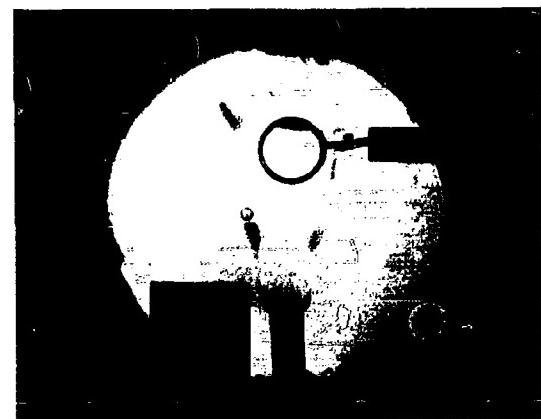


Figure 8. Horizontal knife-edge marking downward deflections.

With a test-object giving rise to large deflections, this is quite a sensitive method of focusing the system. It is recommended as a procedure in preparation for schlieren work and as a first step in the adjustment of the interferometers. (Subsequent steps are discussed below.)

THE SCHLIEREN METHODS (Refs 1-10, 17, 18)

Once the system has been focused, the various schlieren apertures attached to mirror K can be deployed. Figure 7 shows the effect of a vertical knife edge. Only deflections in one horizontal direction are marked. Figure 8 illustrates the effect of a horizontal knife-edge, cutting off all downward deflections. Only where the flame-front has an appreciable horizontal component does it become visible. When the sensitivity is increased by moving the knife-edge so as to cut off more light (Figure 9) the background becomes darker, but a much smaller horizontal component now suffices to make the flame visible.



Figure 9. Horizontal knife-edge marking downward deflection at maximum sensitivity.

For many purposes it is more convenient to display deflection in all directions equally. In Figure 10 this is achieved by a round schlieren aperture. Undeflected light is transmitted, while light deflected in any direction is marked by attenuation. The complementary pattern is produced by a circular stop. Here deflected rays appear on a dark background (Figure 11).

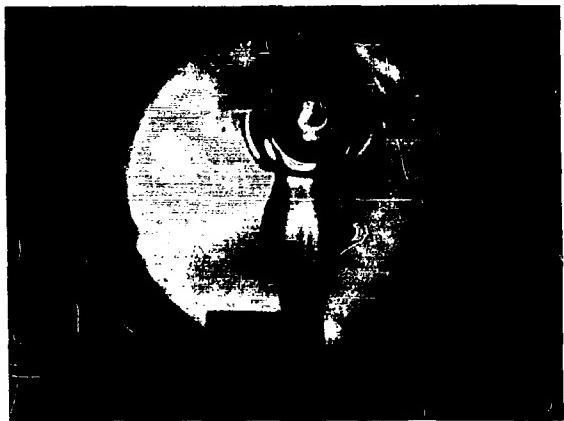


Figure 10. Ring. Symmetrical marking by cut-off.



Figure 11. Circular Stop. Symmetrical marking for transmission.

Color schlieren photographs were obtained using two strips cut from gelatin filters. The two colors - green and red - were arranged either side of (a) a blackened, or (b) an unobscured part of the mirror. Thus in Figure 12 undeflected light is transmitted, deflections in one direction become green, those in the opposite sense red. In Figure 13 the same marking of deflected light is used, but undeflected light is cut off. (In the case of both Figures 12 and 13, the filter strips were not wide enough to intercept the largest horizontal deflections, which occur particularly along the sides of the pipe where the stream broadens.. This is the cause of the bright regions marking those zones.

The next schlieren technique to which the system was adapted was a modified form of the Ronchi (Ref 3) method. This usually employs a grid of opaque lines on a transparent background, the lines being equidistant and of thickness equal to their spacing. They therefore act as a series of knife edges and produce fringes on the record which are loci of equal deflection in one direction. If p is the distance between the lines, then a fringe occurs whenever the angle of deflection (or rather its component perpendicular to the line) is a multiple of (p/f) , where f is the focal length of the schlieren mirror. Instead of using a grid, the opaque elements were drawn on the mirror as a number of concentric circles. The advantages of this are: symmetrical marking in all directions, the appearance of loci as closed contours, and decreased diffraction patterns. Some results are shown in Figures 14, 15 and 16. In Figures 15 and 16, number 3 test objective was studied - with and without an inner pre-mixed flame, respectively. The diameter of the inner opaque ring was such that the first fringe occurred for an angle of about 4×10^{-4} radian -, i. e., 1 min 24 sec of arc.

Unfortunately diffraction, which is always rather troublesome with this method, places an absolute limit on its sensitivity. A grid of as few as 8 lines/cm produces the result shown in Figure 17. The fine structure seen is due to diffraction rather than Ronchi fringes.

An alternative quantitative method (Ref 8) which is much less affected by this difficulty, is the use of a movable slit as a schlieren aperture. The slit is mounted on a calibrated screw, which moves it at right angles to its long dimension. Each slit position yields the locua of points in the test space giving rise to the corresponding angle of deflection (in the direction perpendicular to the slit) and by moving the slit between exposures, the deflection field can be mapped - provided it is stationary in time.

POLAR DIAGRAMS OF DEFLECTION AND SPECIALIZED SCHLIEREN BLINDS (Refs 9, 18)

A film of photographic plate exposed at K will record a polar diagram of deflections in the test space (or over any part of it selected by an aperture at H). On such a diagram, all undeflected light is collected at the point origin, while a deflection θ is displayed as a displacement ($f \theta$) in the direction of deflection, irrespective of where in the test space it occurs. One application of such a record is in the study of turbulent flames (Ref 9) where it has been used to deduce the time-mean randomness of orientation of a corrugated and fluctuating flame-front. More generally, the polar diagram is of interest because it is the pattern that is being partially cut off by the schlieren aperture. When it is known, it is possible to design specialized schlieren apertures, constructed to make the system particularly sensitive (or the reverse) to a select group of phenomena. Indeed, the record of a polar diagram on a photographic plate may be used in this capacity as



Figure 12. Color schlieren. Undeflected light transmitted.

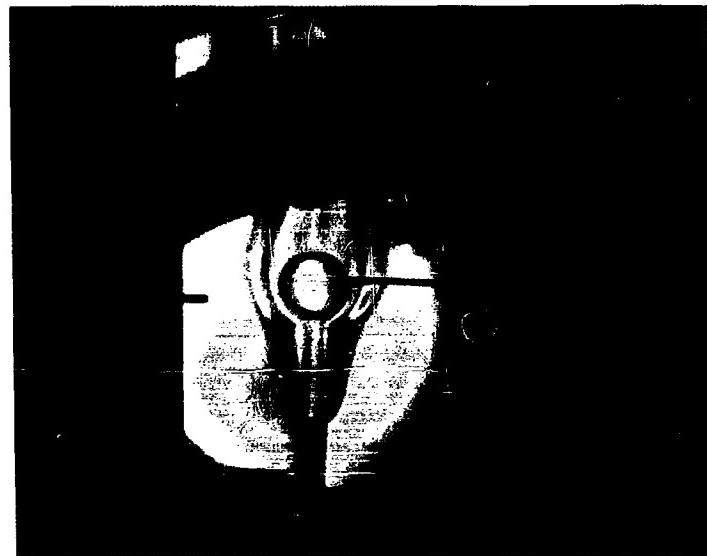


Figure 13. Color schlieren. Undeflected light cut-off.

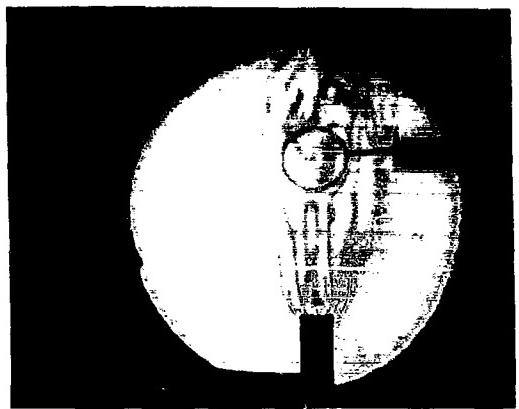


Figure 14. Center-symmetrical "Ronchi" (a new development). Each fringe corresponds to about 4×10^{-4} radians (84 sec arc) in any direction

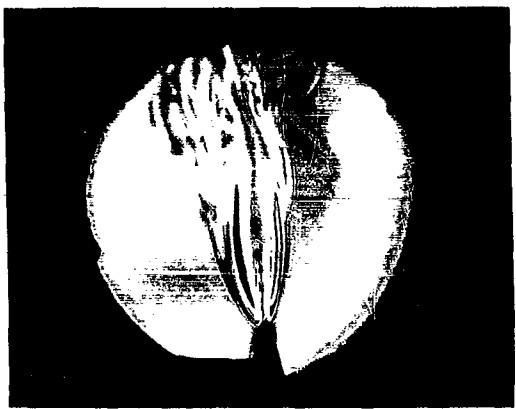


Figure 15. Center-symmetrical "Ronchi" Schlieren. Bat's wing flame - partly



Figure 16. Center-symmetrical "Ronchi" Schlieren. Bat's wing diffusion flame.



Figure 17. Excessive sensitivity in "Ronchi" Schlieren lead to diffraction, which makes pattern irresolvable.

a negative or a positive, according to whether it is desired to enhance or to suppress its visualization in the presence of other phenomena.

The polar diagram (taken at right angles to the optic axis) of test object (3) is shown in Figure 18. The pronounced horizontal lines are caused by the predominately vertical sides of the flame, while the very much weaker loop underneath originates in the region around the apex of the flame. Figure 19 shows the polar diagram of deflections caused by test object number 4. The grating was, of course, oriented with its rulings at right angles to the line dots in Figure 19. Since all the deflections are in one plane, this test object lends itself particularly readily to a simple illustration of the "specialized schlieren aperture" principle. Thus in Figure 20, the strips of color filters were so oriented with respect to the polar diagram that light deflected (or rather diffracted) in the appropriate plane was blue, while undeflected rays remained green.



Figure 18. Polar diagram: Bat's Wing flame.



Figure 19. Polar diagram: Ronchi grid, 60 lines/in

In Figure 21, on the other hand, light deflected in the selected direction is blue, but was allowed to overlap the red filter to some extent, resulting in a violet tint. It will be obvious that it is possible not only to design a schlieren aperture which will concentrate on (or suppress) a grating oriented with its lines in a particular direction; but that by using the appropriate spacing of the maxima (Figure 19), the system can be made selective with respect to one particular line-spacing.



Figure 20. Color polar diagram. Undeflected light is green.



Figure 21. Color polar diagram. Deflected light is blue.

QUANTITATIVE DEFLECTION MAPPING (Refs 9, 14-18)

In the measurement of deflection, and hence, of refractive index fields, it is much more accurate to measure a shape than an intensity of blackening on a photographic emulsion. In this section, simultaneous visualization of the test space will therefore be sacrificed and the record will consist of some distorted pattern. These shapes are then to be compared with the undistorted original "reference marks on the wave front". This undistorted shape is usually deducible by interpolation from the undeflected extremities of the lines and, from these, the displacement can be measured. If the direction of deflection is known in each location (or can be deduced by direct, schlieren, or "polar diagram" photography of the test space) the simplest convenient pattern is a series of initially straight and parallel lines. If a grid of intersecting lines is used instead, a direct check on direction of deflection becomes available in the displacement of the points of intersection. The use of both kinds of screens will be illustrated. The methods of interpretation - i. e., the process leading to the deduction of a refractive index field - has been discussed elsewhere and will not be repeated in this report which is primarily concerned with technique.

The simplest and most obvious use of such a screen is in the form of a parallel-light shadow. Thus in Figure 1, the screen could be at H or Q and the receptor at J. Under these condition, the angle of deflection is the displacement divided by the distance between receptor and test object, or by the distance between receptor and screen, if that is the smaller. In this latter case it is necessary to use the measured angle also to deduce the position in the test space at which the measured deflection originates.

This method is accurate for large angles of deflection caused by large optical path gradients. For example, it is ideal with a large pre-mixed flat flame and it has been used extensively with a simple screen of inclined slits. In the present instance, however, we are concerned to make it overlap the range of interferometry by as large a margin as possible and we must therefore, consider its limitations. These are due to diffraction at the marking screen, which results in a limiting resolving power. The limit is set by the relative magnitudes of the angle of deflection and the angle subtended by the uncertainty in position on the record, caused by the spread of the diffraction pattern. As the displacement per unit angles is increased - for instance by increasing the distance to the receptor - the uncertainty grows in proportion, and no increase in accuracy is achieved. This limit is aggravated by an indeterminacy in the position of the deflection's origin. The narrower the slit is made, in order to define this position accurately, the wider its diffraction pattern and, hence, the less accurate the measurement of the magnitude of deflection. These defects become noticeable for deflection angles less than about 10^{-3} radians; there are two possible methods of alleviating them.

The more fundamental method is to use a "physical optics" principle for marking the wave-front - rather than the "geometric" one of casting shadows. A principle that lends itself readily to incorporation in the present system is the use of a half-wave step^(Ref 14) as a reference mark. Consider two halves of a transparent, parallel-sided plate, one half of which is slightly thicker than the other. The difference in thickness is such that the wave-front emerging from one part is half a wave length out of phase with the other part, and the step lies along a straight line. Along the plane containing this line and the perpendicular to the

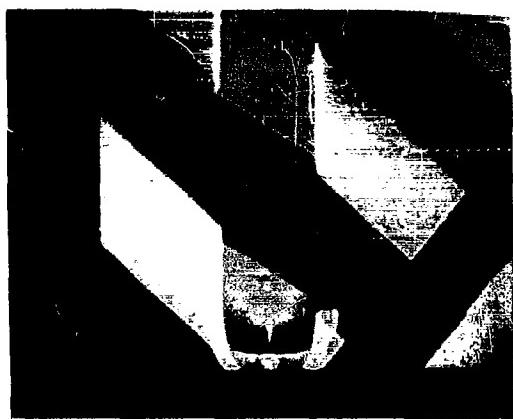


Figure 22. Parallel light shadow.
Diffraction pattern due to
knife edge.

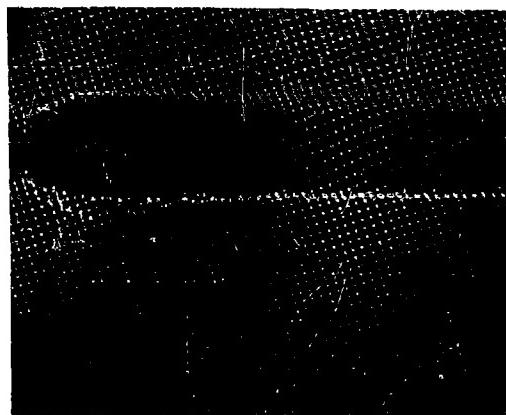


Figure 23. Parallel light shadow.
Diffraction pattern due to
grid. Bat's wing flame.

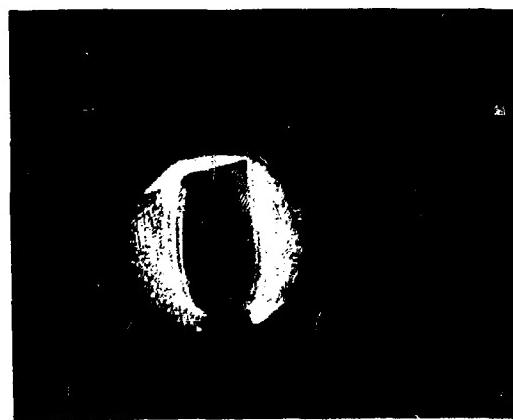


Figure 24. Parallel light shadow.
Diffraction pattern due to
closed space grid. Bat's
wing flame.



Figure 25. Parallel light shadow.
Half wave step plate.
Bat's wing flame.

plate, destructive interference of the two parts of the wavefront produces a sharp line for quite an appreciable distance beyond the step.

A glass plate, 13 cm square, coated with 6 parallel strips of magnesium fluoride - each half a wavelength thick, 1 cm wide, and 1 cm removed from the next strip - was procured for the optical system. This marks the wave front with a reference grid of 12 straight lines over a square area of edge - length approximately equal to the radius of the schlieren mirrors.

Figures 22 - 25 are deflection mapping records taken in a parallel beam. Whilst the use of a slit produces a diffraction pattern which is the wider the narrower is the slit, marking by shadows is always limited in this manner. The irreducible minimum is the diffraction pattern due to a knife edge - Figure 22 - to which that of a slit tends as slit-width tends to infinity.

When repetitive patterns are used at small separation, it is often possible to use the resulting diffraction pattern to better effect than would be possible with a single element. Thus the deflections in Figure 23 are displayed using the diffraction pattern due to a wire gauze. The diameter of the strands was about 0.3 mm, as compared with their separation of 1.5 mm. Yet in the diffraction pattern of Figure 23 the bright lines (which, on geometric theory, would correspond to the spaces) are narrower; this may be compared with Figures 26 - 28 in which the same grid was used in a different position. In zones of large optical path gradients (and hence large deflections), the diffraction patterns become difficult to read because of phase-difference effects. If the grid spacing is too close - Figure 24, using a grid of 60 lines/in. - the record becomes illegible.

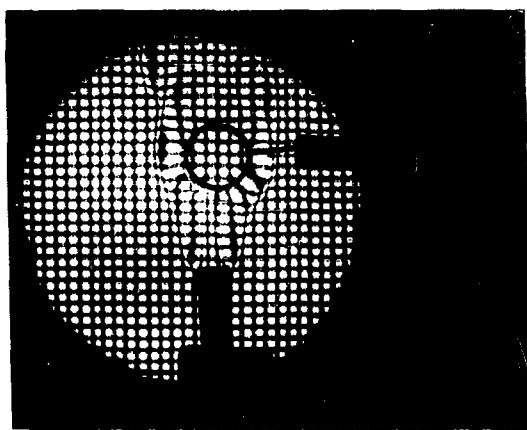


Figure 26. Deflection mapping,
square grid.

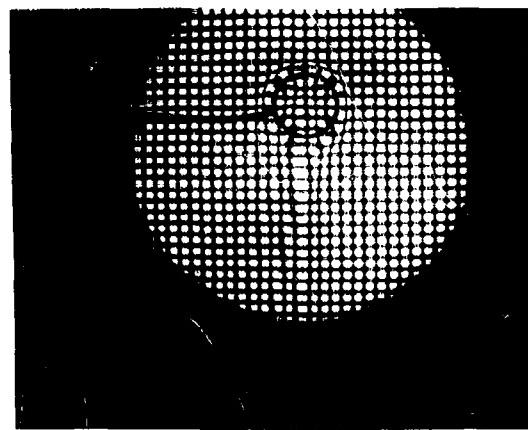


Figure 27. Deflection mapping,
square grid, heated pipe

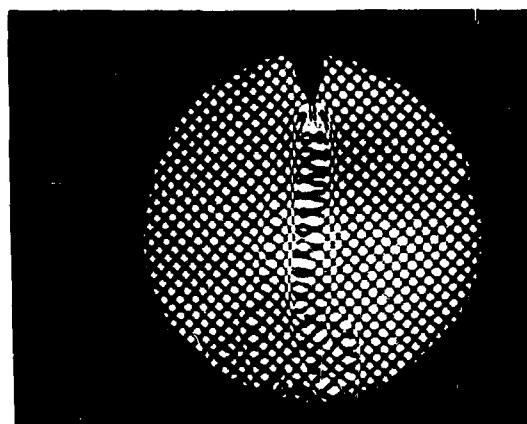


Figure 28. Deflection mapping,
square grid, Bat's wing
burner

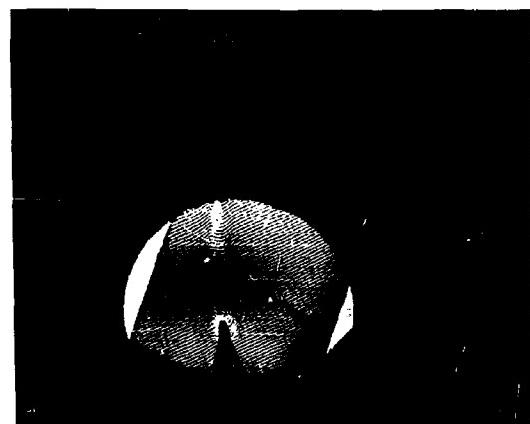


Figure 29. Deflection mapping, 60
lines per inch grating,
Bat's wing flame.

The record obtainable by the half-wave-step plate is shown in Figure 25. As concerns its legibility for displacement measurements, it is a considerable improvement over the other methods of marking, using a parallel beam.

The other method of improving legibility involves the use of a lens and/or other optical elements before the receptor. The theory of interpretation is then not quite so obvious, but the necessary calculation (Refs 16 - 18) is simple. The principle of the method is that, if the test space and marking screen are at different distances from the lens and therefore represented at different magnification, the proportionality ties between magnitude of displacement and width of diffraction pattern is broken. An additional degree of freedom thus becomes available for improving the record.

It might appear, at first sight, that the optimum arrangement is that in which the marking screen is focused on the receptor, whilst the test space is not. In the absence of deflections in the test space, this indeed results in the disappearance of diffraction patterns on the record. In the most important zones, however, where deflections occur, the record is broken up into fringes. These occur as a result of the recombination, after traversal of different optical paths in the test space, of the diffracted "rays." Figures 26 - 34 were taken, on the contrary, with the test space approximately focused on the receptor. The marking screen was at position N.

Figures 26 - 28, taken with the gauze described earlier, appear superficially attractive. Closer examination, however, reveals that in zones of large deflection, the spread of the diffraction pattern would impair the accuracy of displacement measurements. Figures 29 and 30 were taken using the 60 lines/in. grating.

It will be seen that, at this separation from the screen, the lines can be followed through in most regions and measurements of displacements become possible.

Combination of this optical system with the slide of half-wave steps undoubtedly produces the sharpest results, Figures 31 - 34. The nature of the test objects in these photographs is self-evident. Figure 32 shows the record obtained when the system is slightly de-focused, so that shadows begin to re-appear where deflections are greatest. Figures 33 - 34 show how well the sharpness of the lines is maintained in the presence of very large deflections. In Figure 34, one of the deflected lines curves to a particularly sharp peak.

INTERFEROMETRY AND ITS COMBINATION WITH OTHER METHODS

The system on which the enclosed illustrations were obtained was that shown in Plan II of Figure 1. Figures 35 - 37 show typical interferograms. The adjustment of the interferometer is very simply carried out by moving the second grating, using the appearance of fringes as a guide. This grating was gradually moved away from the focus in order to produce the increase in inclination of the two wave fronts and, hence, closer fringe spacing, in going from Figure 35 to Figure 37. In all these experiments, the flame was extinguished except for a small pilot, and in Figure 36 the tube suspended above it was at quite a low temperature.

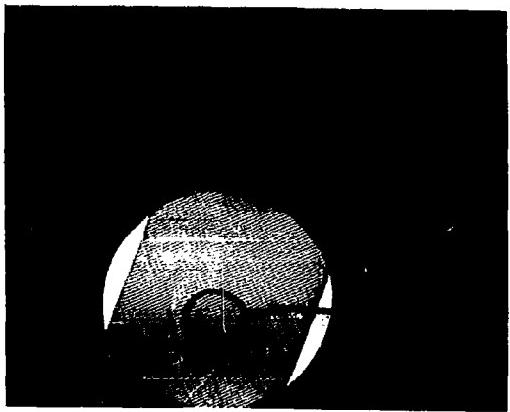


Figure 30. Deflection mapping, 60 lines per inch, heated pipe.

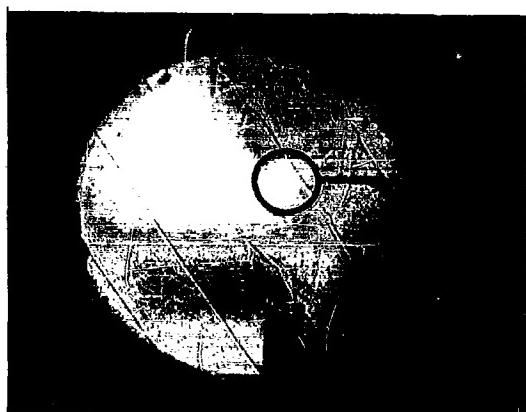


Figure 31. Half-wave step plate before bellows, flame focused.

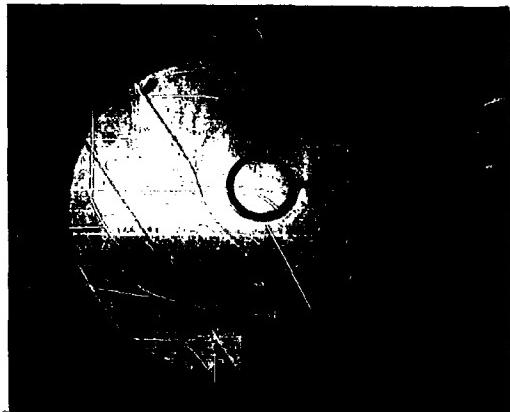


Figure 32. Half-wave step plate before bellows, flame nearly focused.

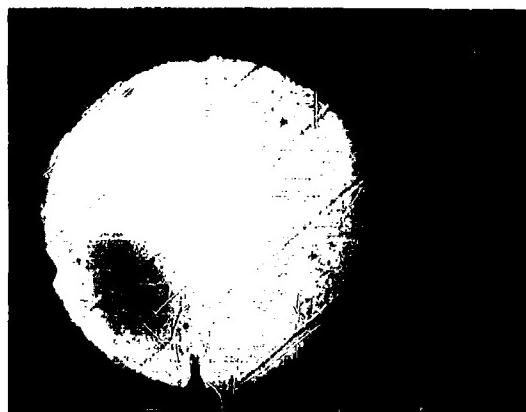


Figure 33. Half-wave step plate before bellows, Bat's wing flame focused.

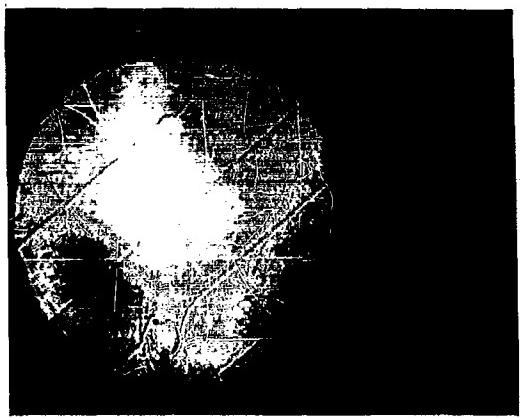


Figure 34. Bat's wing flame focused showing particularly sharp deflection peak with half-wave plate.



Figure 35. Interferogram of heated ring.

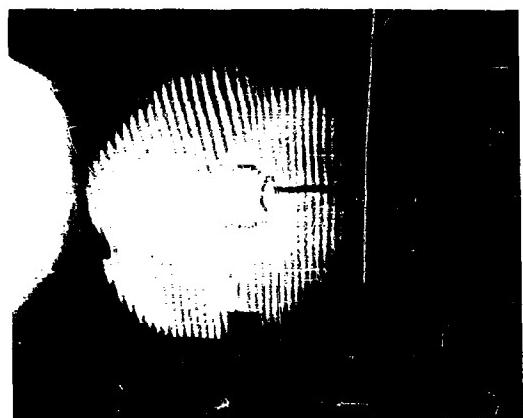


Figure 36. Interferogram of heated ring, closer fringe spacing.

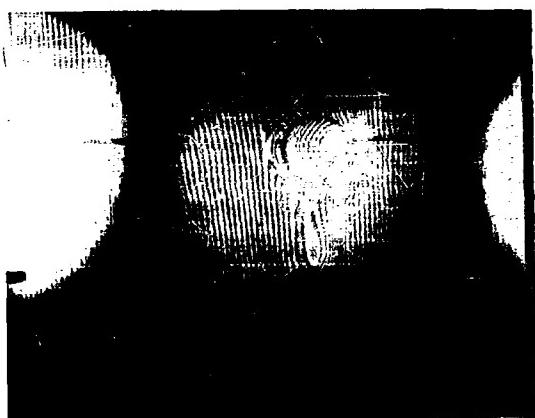


Figure 37. Interferogram of heated ring, still closer fringe spacing.

It is sometimes convenient to combine interferometry with one of the other methods described. Thus, it is possible to superimpose color schlieren upon it and mark fringes in zones where deflections occur by different colors. This method is based on two of the unusual properties of the interferometer. The first is that the beam traversing the test zone (but not, of course, the other beam) forms a polar deflection diagram at the focus of the second schlieren mirror and selected deflection can be marked there by color filters before recombination. It is important, however, that the optical thickness through which the deflected rays pass should not differ unduly from that at the undeflected focus. Fringes will, of course, disappear wherever such differences occur between test and reference path. Even when the thicknesses are small enough for this not to happen, an additional cause of phase variation with position in test space will have been introduced. The best method is therefore to produce the color variation by means of a single filter of constant (small) thickness, whose color varies with position in the desired manner. Color transparency film lends itself readily to the production of such a filter. The second property of the interferometer which makes this method possible, is its ability to produce fringes over a large range of orders without requiring monochromatic light. This attribute, which has been discussed in detail elsewhere (Refs 20, 18), was mentioned above. It is illustrated in Figure 38*, in which all the wave lengths of the mercury arc were used. Whilst the colors are separated, the fringes remain discernible and continuous in the several orders of the second grating.

* The color reproduction is very poor, however.

A less spectacular, but quantitatively more useful method, is the association of interferometry with deflection mapping. Generally interferometry becomes difficult to apply when optical path gradients are steep enough to produce large deflections, and vice versa. To illustrate the overlap of the two types of method, a wing-flame was rotated until both methods gave reasonable accuracy over most of the field of view. The flame was focused on the receptor and the plate of half-wave steps was in position N. The result is shown in Figure 39.

This kind of record yields, simultaneously, the distribution of optical path, and of its first derivative with respect to distance. It is ideal for composite refractive index fields which involve both steep and gradual variations, particularly in cases where movement or fluctuation of the test phenomenon makes it impossible to apply the two methods separately to the same refractive index field.



Figure 38. Color separation in fringes over several diffraction orders.

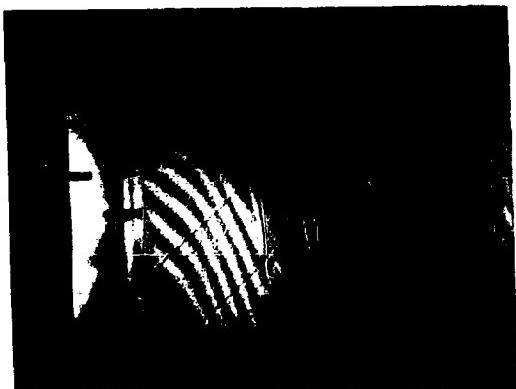


Figure 39. Combined deflection and interferogram patterns for Bat's wing burner.

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A relatively inexpensive optical system is described which is capable of interferometry deflection mapping, shadowgraphy and the entire range of schlieren recording. It is easy to set up, requires only minor adjustments to convert it from one function to another.

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